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**RESEARCH DEPARTMENT**

**REPORT**

# DIGITAL VIDEO
# differential coding of PAL
# colour signals using same-line and
# two-dimensional prediction

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# DIGITAL VIDEO: DIFFERENTIAL CODING OF PAL COLOUR SIGNALS USING SAME-LINE AND TWO-DIMENSIONAL PREDICTION

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## Summary

*Methods for reducing the bit-rate required for digital coding of System I (PAL, 625-line, 5·5 MHz) video-signals by means of differential pulse-code modulation (d.p.c.m.) are discussed. In the d.p.c.m. codes which have been investigated, each codeword indicated the difference between a sample of a video signal and a prediction of this sample value based on samples already transmitted in the same and/or previous line-periods. A novel technique is described for obtaining a good prediction from the previous line of a PAL colour video-signal. With a view to finding a system giving broadcast-quality pictures, various d.p.c.m. systems were examined; these required the transmission of three to six bits per sample at a sampling frequency of three times the PAL colour-subcarrier frequency, i.e. 13·3 MHz. Subjective tests and measurements of signal-to-quantising-noise ratio have been performed on these systems.*

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## V.G. Devereux, M.A.

## 1. Introduction

In order to reduce the cost of transmitting and recording broadcast-quality video signals encoded in digital form, there is a demand for improved methods of coding to reduce the bit-rates below the figure of 100-120 Mbit/s required for linear pulse-code modulation.[1] One of the most useful bit-rate reduction techniques for video signals is differential pulse-code modulation (d.p.c.m.).[2] With this technique, the video signal is sampled at regular intervals and each digital code-word which is transmitted represents the difference between a sample value and a prediction of this value obtained from previously transmitted samples. An earlier report[3] has described work carried out to examine the possibility of reducing the bit-rate required for System I (PAL, 625-line 5·5 MHz) video-signals by means of d.p.c.m. systems in which the predicted value of each sample is given by the sample occurring one colour-subcarrier period earlier. A better prediction can often be obtained by considering also the value of spatially-adjacent samples on the previous lines either in the same field, or in previous fields. Predictions based on two or more samples occurring on different lines in the same field of a picture are often referred to as two-dimensional predictions.

With PAL video signals, prediction from samples in the previous line in the same field is complicated by the 180° phase reversal of the $v$ chrominance-component for alternate line periods.* This report describes a novel technique for overcoming this problem when the sampling frequency is locked to three times the colour-subcarrier frequency. DPCM equipment incorporating a two-dimensional predictor based on this technique has been constructed and results are given of subjective tests concerning the picture impairment introduced by this equipment. For comparison, similar tests were carried out using d.p.c.m. coding with same-line prediction and p.c.m. coding. Finally results are given of objective measurements of the quantising and prediction errors obtained with d.p.c.m. coding of PAL signals. These measurements are used to compare the visibilities of quantising noise produced by d.p.c.m. and p.c.m. coding of video signals, and to analyse the quantising laws used in the subjective tests.

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* The chrominance component of a PAL signal is given by the sum of two quadrature subcarrier signals usually denoted by $u$ and $v$ which are defined by the equations

$$u = U \sin 2\pi f_{sc} t$$

$$v = \pm V \cos 2\pi f_{sc} t$$

where $U$ and $V$ are proportional to $B\text{-}Y$ and $R\text{-}Y$, $Y$ being the luminance component of the video signal and $B$, $R$ are the blue and red primary colour signals; $f_{sc}$ is the subcarrier frequency. The sign of $v$ is + and − during alternate line periods.

## 2. General principles of differential pulse-code modulation

As mentioned above, each digital code-word produced by d.p.c.m. represents the difference in magnitude between a sample of a video signal and a prediction of that sample derived from previously transmitted samples. Assuming that an efficient prediction system has been adopted, small differences are more probable than large differences. Therefore, if the number of difference values which can be transmitted is fixed, the r.m.s. value of the quantising error introduced by the d.p.c.m. coder is minimised by employing a non-linear quantising law, so that small differences are encoded more accurately than large differences. By arranging that the d.p.c.m. coder and decoder both make the same prediction of each sample value, a signal sample can be recovered in the decoder by adding the appropriate transmitted difference to the predicted sample-value.

A block diagram of a d.p.c.m. coder and decoder is shown in Fig. 1. Although the operations shown in Fig. 1 can be performed on analogue samples of the video signals, in the present application the input and output sampled signals are in 8-bit p.c.m. form. $A$ represents the value of a sample of the video signal applied to the coder, $B$ represents
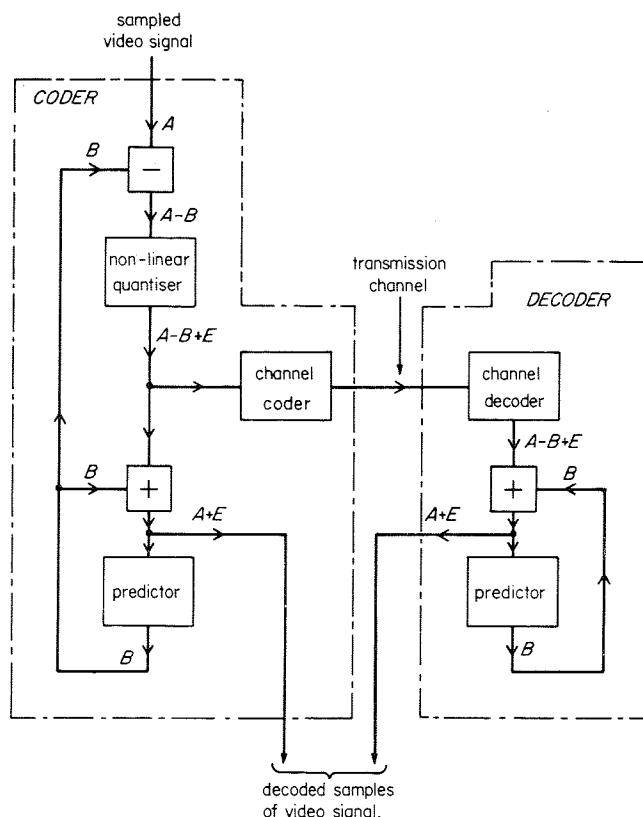


Fig. 1 - Block diagram of a d.p.c.m. coder and decoder

the predicted values of this sample and $E$ represents the quantising error added to the difference signal $A-B$ by the non-linear quantiser. The channel encoder converts the output signal $A-B+E$ from the non-linear quantiser into a suitable transmission code, and the channel decoder performs an inverse process to re-establish the same value of $A-B+E$ in the decoder. The coder and decoder both integrate this quantised difference signal in identical feedback loops containing the adder and predictor. Providing that the predicted sample value $B$ in the decoder has been set to the same value as in the coder for one particular sample, all following output sample values $A+E$ and predicted sample values $B$ will be identical in both the coder and decoder unless a transmission error occurs. With video signals, the predicted signal is normally reset to its correct value in each line-blanking interval.

For monochrome signals, a simple but effective method of prediction uses the decoded value of the previously transmitted sample as the prediction for the following sample. In this case, the predictor would consist of a delay of one sample period, assuming delays in the adder, subtractor and non-linear quantiser are negligible. With a composite colour-signal, this form of prediction is unsatisfactory because the presence of a colour subcarrier produces many large differences between adjacent samples which would cause large quantising errors in coloured areas of a picture. The simplest way to solve this problem is to sample at a multiple of the colour-subcarrier frequency and then to take differences between samples separated by one period of the colour subcarrier. This form of prediction for d.p.c.m. coding of PAL video signals has been discussed elsewhere for a sampling frequency of three times the colour-subcarrier frequency.[3,4]

## 3. Use of samples from previous line for prediction with composite colour video-signals

One method of improving the prediction is by means of a two-dimensional predictor which makes use of samples from the previous line as well as from the same line as the incoming sample. A block diagram of a simple two-dimensional predictor is shown in Fig. 2. Delay $D_1$ would normally be equal to one sample period for monochrome video signals or one colour-subcarrier period for composite colour signals; for delay $D_2$, a simple delay of about one line-period is suitable for monochrome signals and NTSC colour signals, but for PAL colour signals a more complex switched delay is required as discussed below. The
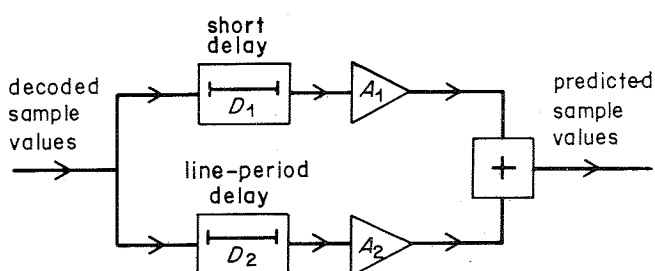
weighting of the same-line and previous-line sample values is determined by the amplifier gains $A_1$ and $A_2$, suitable weighting coefficients being of the order of one half. Results obtained using this form of predictor for monochrome signals have been described elsewhere.[5] Results obtained for PAL colour signals using the method described below are given in Section 6; an alternative method using an analogue 'PAL modifier' to give 'chrominance-corrected prediction' has been described by Thompson.[4]

With NTSC colour video-signals a good prediction could be obtained from a spatially-adjacent sample in the previous line by sampling at a multiple of subcarrier frequency and by choosing a sample separated in time from the incoming sample by an integral number of cycles of the subcarrier. With PAL colour video-signals, however, previous-line prediction is complicated by the $180°$ phase alternation of the $v$ chrominance components which occurs on alternate lines. This difficulty with previous-line prediction of PAL signals can be largely overcome however by suitably adjusting the timing as well as the frequency of the sampling instants.[*6] The technique is applicable to sampling frequencies of the form $(n/m)f_{sc}$ where n and m are small positive integers and $f_{sc}$ is the colour subcarrier frequency. For such frequencies, samples in a plain coloured area of a picture occur at n different phases of the subcarrier (assuming n and m have no common factors). In order to simplify previous-line prediction, the timing of the sampling instants should be adjusted so that if one of the subcarrier phases at which samples occur is at an angle $\phi$ relative to the $u$ axis, there should also be samples occurring at an angle $-\phi$. If this condition is satisfied, the subcarrier phases at which samples occur are the same for both states of the $v$-axis switch but the sequence in which these phases occur is reversed.

Appropriate sampling instants for a sampling frequency of $3f_{sc}$ corresponding to $\phi = 0$, $+120°$ and $-120°$ are indicated in the waveforms of Fig. 3(a) and the vector diagram of Fig. 3(b). From these diagrams, it can be seen that if the magnitude of successive samples in a uniformly coloured area during one line period are $O$, $A$, $B$, $O$, $A$, $B$, etc., then the reversal of the sign of the $v$ chrominance component in the following line period gives the same sample values but in the reversed sequence $O$, $B$, $A$, $O$, $B$, $A$, etc., where $O$ corresponds to samples taken at zeros of the $v$ chrominance component ($\phi = 0$). Alternatively, the subcarrier could be sampled at the phases corresponding to $\phi = 180°$, $+60°$ and $-60°$. (N.B. $\phi = 180°$ also corresponds to a zero of the $v$ chrominance component.)

If a PAL signal corresponding to a plain coloured area is sampled at $3f_{sc}$ in either of the preferred sets of phases described above, the resulting pattern of sampling points of magnitude $O$, $A$ and $B$ will be as shown in Fig. 4. The three parts (a) (b) and (c) of this figure show the same pattern of sampling points but indicate three different choices of samples for use in previous-line prediction. All three forms of prediction may be achieved by means of the delay network shown in Fig. 5. In this figure $T$ represents



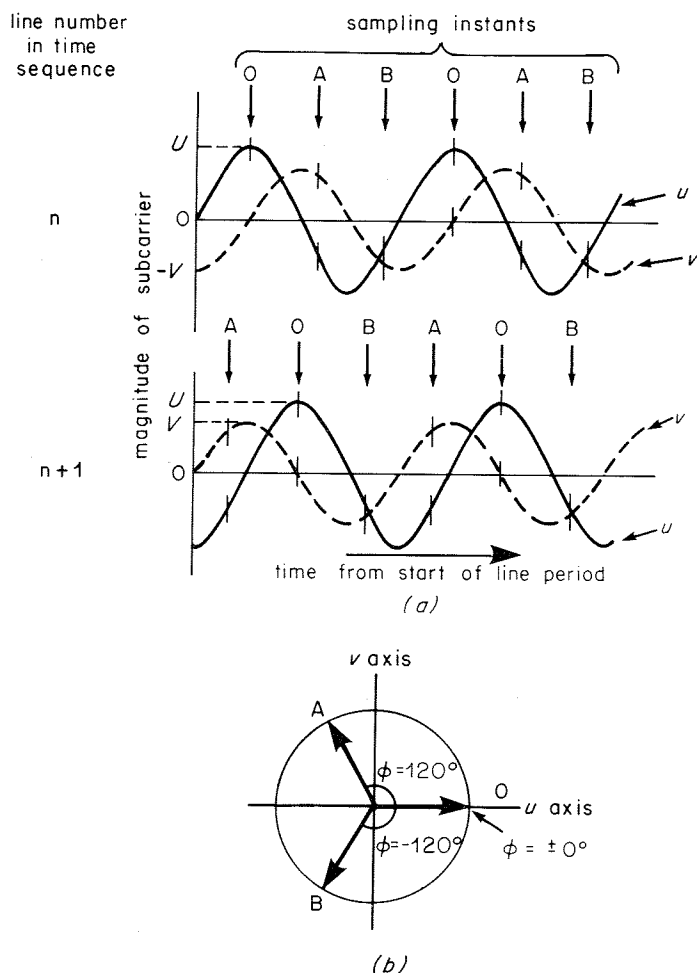*Fig. 2 - Block diagram of a two-dimensional predictor*

Fig. 3 - Phase of $3f_{sc}$ sampling instants relative to colour subcarrier components of a PAL video signal for use with previous-line prediction

(a) Timing diagram        (b) Vector diagram

a delay of one sample-period and N is an integer such that NT is approximately equal to one line-period. Re-ordering of sample values appropriate to the following line-period is performed by means of switch S1 which rotates in an anti-clockwise direction moving one position per sample. The phase of switching with respect to the O, A and B samples of colour subcarrier must be adjusted so that the O samples are delayed by an integral multiple of 3 sample-periods. For example, if N = 850, then the switching phase must be adjusted so that the O samples are delayed by 2T in the switched delay (852 = 3 x 284). The arrows in Fig. 4 indicate the spatial displacement, line by line resulting from delays of O, A and B samples obtained when N = 849, 850 and 851. (At a $3f_{sc}$ sampling rate, the number of samples per line period is very nearly equal to 851¼.)

For a correctly adjusted picture raster, the ratios of previous-line prediction distances to the distance $O_0O_1$ occupied by one cycle of subcarrier in the same line, are given by:—

$$O_2O_0 = 0.96 \, O_0O_1$$
$$A_2A_0 = 0.73 \, O_0O_1 \quad \Big\} \quad N = 849 \ (\text{See Fig. 4}(a))$$
$$B_2B_0 = 0.61 \, O_0O_1$$



(a) N = 849

(b) N = 850
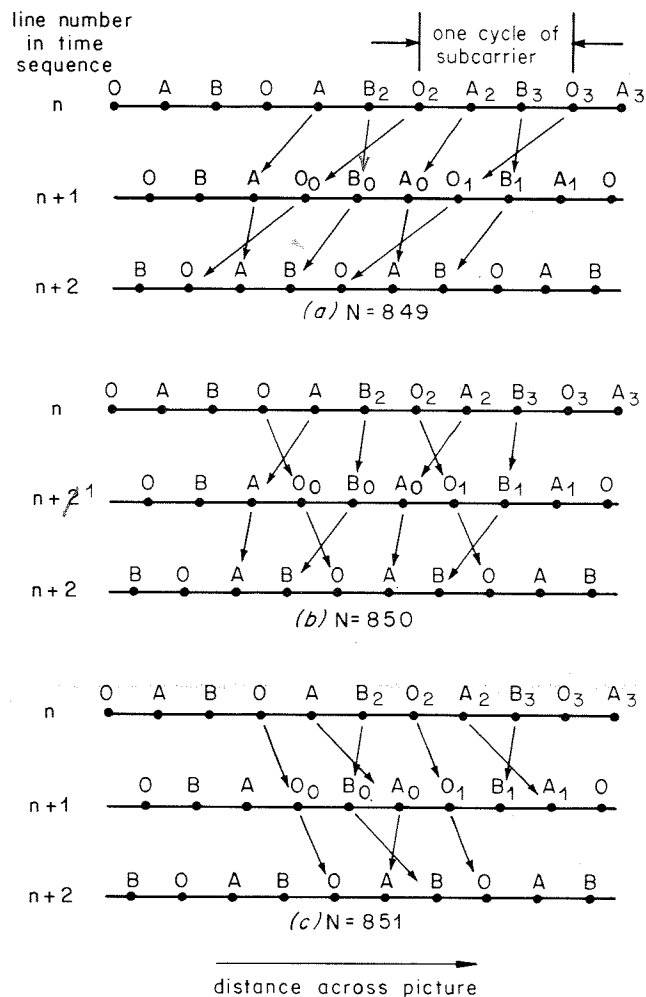
(c) N = 851

distance across picture

Fig. 4 - Possible forms of previous-line prediction for PAL signals

Diagrams show position of $3f_{sc}$ sampling points on three successive scan-lines in one field period. Horizontal and vertical distances drawn to scale for correctly adjusted raster. N refers to the number of sample periods in the fixed delay line of Fig. 5
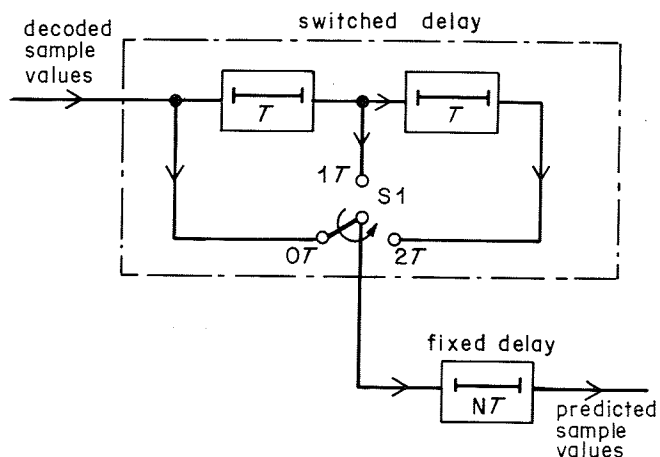


Fig. 5 - Previous-line predictor for PAL signals sampled at $3f_{sc}$ in preferred phases. T indicates a delay of one sample period

$$O_2 O_1 = 0.65 \, O_0 O_1$$
$$A_2 A_0 = 0.73 \, O_0 O_1 \quad \Bigg\} \quad N = 850 \ (\text{See Fig. } 4(b))$$
$$B_2 B_0 = 0.61 \, O_0 O_1$$

$$O_2 O_1 = 0.65 \, O_0 O_1$$
$$A_2 A_1 = 0.84 \, O_0 O_1 \quad \Bigg\} \quad N = 851 \ (\text{See Fig. } 4(c))$$
$$B_2 B_0 = 0.61 \, O_0 O_1$$

The distance $O_0 O_1$ has been used as a reference since it was the prediction distance used in previous work on d.p.c.m. coding of PAL signals employing only same-line prediction.[3] At a sampling frequency of $3 f_{sc}$, $O_0 O_1$ corresponds to three sample periods and therefore the use of $O_0$ to predict $O_1$ (and $B_0$ to predict $B_1$ etc.) will be referred to as third-previous-sample or $3T$ prediction.

Examination of the ratios given above shows that the mean previous-line prediction distance is at a minimum for N = 850 indicating that this is the optimum value of N for previous-line prediction alone.

For two-dimensional prediction, provided by the mean value of the third-previous sample on the same line and a sample from the previous line, the optimum value of N is not so obvious, being a choice between N = 849 or 850. The only difference between these two predictions is the previous-line prediction of the $O$ samples. For N = 849, $O_3$ is used in the prediction of $O_1$; for N = 850, $O_2$ is used. Although $O_2$ is closer than $O_3$ to $O_1$, the mid-point between $O_2$ and $O_0$ is farther from $O_1$ than is the mid-point between $O_3$ and $O_0$. Measurements of r.m.s. prediction errors (see Section 9) showed differences no greater than about 0.3 dB when N was changed from 849 to 850 with several different slide pictures, the value of N giving the smallest error being dependent on the picture material; subjective tests also gave inconclusive results. For the series of tests described in Section 6, N was chosen to be 850.
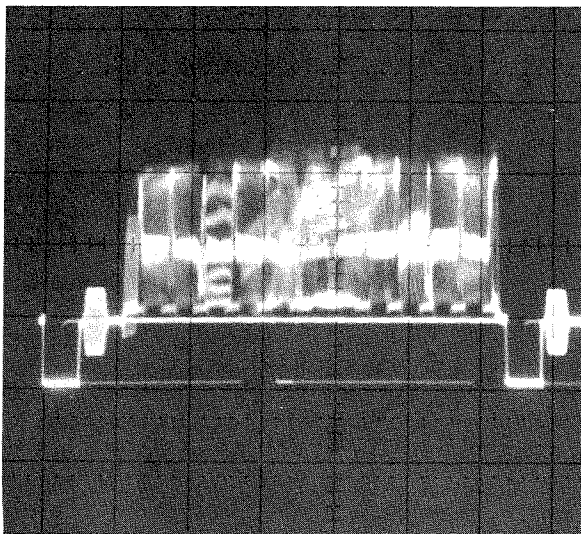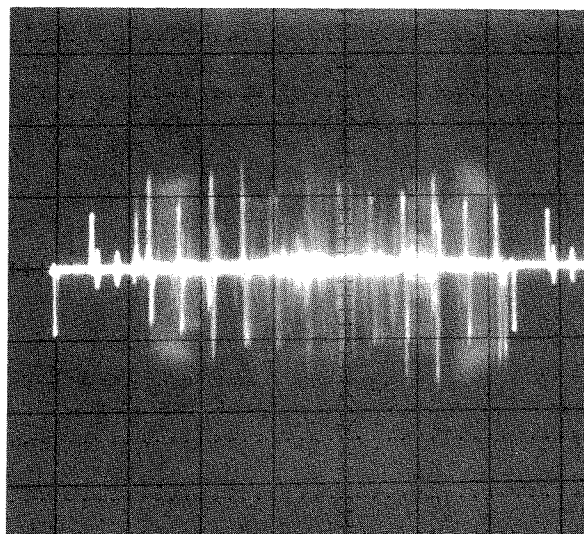


(a)



(b)



(c)



(d)

*Fig. 6 - Displays of actual minus predicted signal, to illustrate prediction errors obtained from Test Card F*
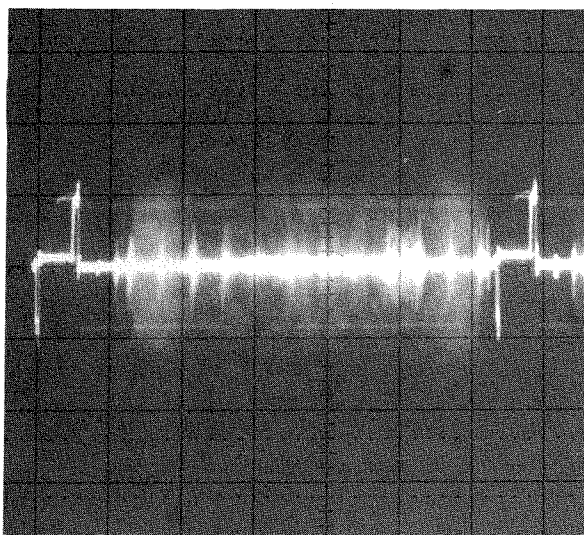
(a) Original picture    (b) '3T' same-line prediction error    (c) Previous-line prediction error    (d) '2D' prediction error
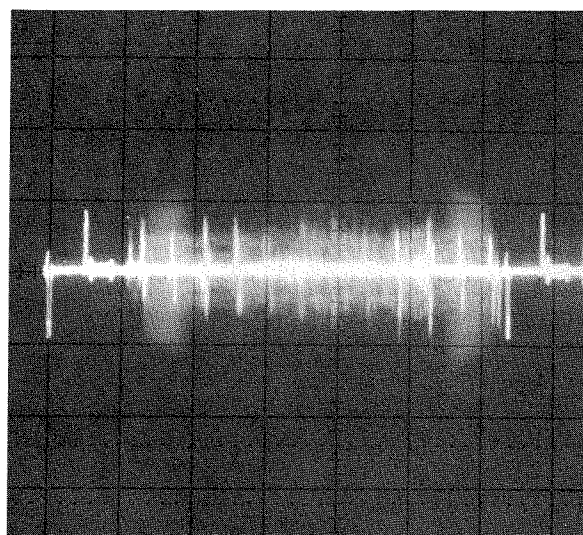
(a)



(b)



(c)



(d)

*Fig. 7 - Waveforms of prediction errors obtained from Test Card F*

(a) Original signal     (b) '3$T$' same-line prediction error     (c) Previous-line prediction error     (d) '2D' prediction error

Horizontal scale: 1 div. = 10 $\mu$s.   Vertical scale:   1 div. = 64 quantum levels. (p.c.m. conversion range = 256 quantum levels)

## 4. Comparison of prediction errors for different forms of prediction

The different forms of prediction error ($A-B$ in Fig. 1) obtained with same-line, previous-line and two-dimensional prediction applied to a PAL video signal representing a Test Card are illustrated in Figs. 6 and 7. For both these figures, the sampling frequency was equal to 3 $f_{sc}$; same-line prediction was given by a delay of 3$T$, previous-line prediction was given by a switched line-delay with N = 850, and two-dimensional prediction was given by half the sum of these same-line and previous-line predictions.

It can be seen from these figures that with same-line predictions, the largest prediction errors occur at vertical edges in picture detail while previous-line prediction gives maximum errors at horizontal edges. With two-dimensional prediction, errors occur on both horizontal and vertical edges but the r.m.s. error is reduced compared with that obtained with either same-line or previous-line prediction alone.

The step of about 5 $\mu$s duration, with a pulse at both ends, in the mean level of the previous-line prediction error shown in Fig. 7(c) was caused by a clock-blanking process

applied to the line-delay during the video line-blanking interval as described in Section 5. This clock blanking does not noticeably affect the two-dimensional prediction error as the predictor was automatically switched to same-line prediction during this interval.

For both Figs. 6 and 7 the amplitude of the video signal in the p.c.m. coder was adjusted so that a 100% colour bar signal would just fill the conversion range.

## 5. Experimental equipment

The d.p.c.m. coder section of the block diagram shown in Fig. 1 has been constructed. The channel coder and d.p.c.m. decoder were not constructed since the purpose of the equipment was to examine the subjective effect of d.p.c.m. quantising errors and this can be achieved by displaying the output signal $A+E$ from the coder. One penalty paid for the omission of the decoder was that it was not possible to examine the effect of errors in a transmission channel.

For accuracy and ease of instrumentation, the signal processing throughout the d.p.c.m. coder was digital; all the signals represented in terms of $A$, $B$ and $E$ in Fig. 1 consisted of 8-bit p.c.m. signals in parallel form. In the work

on d.p.c.m. systems the 8-bit p.c.m. coder was operated without 'dither'.[1] Details of the arithmetic operations occurring within the coder have been discussed in a previous report concerning d.p.c.m. coding using same-line prediction.[3]

The non-linear quantiser could be adjusted by front-panel switches to give a variety of quantising laws. The positive halves of the laws used in the subjective tests described in Section 6 are illustrated in Fig. 8; the negative halves have a similar characteristic apart from minor differences caused by instrumental considerations. The setting of the output levels was determined by subjective assessment of picture quality for a variety of slide pictures. Possible improvements to the characteristics based on theoretical laws giving minimum quantising distortion are discussed in the Appendix. The relative advantages of the two laws given for 6 bits per sample are discussed in Section 8 and the Appendix; Law 1 was used in the subjective tests.

The characteristic for 6 bits, Law 1, continues for large differences with one output step for every change of eight input levels, up to the maximum possible difference values of $\pm255$.* As a result, this law has more than 64

* Throughout this report, magnitudes of signals are expressed in terms of the decimal equivalents of the 8-bit binary numbers used to represent the signals. In these units the input video signal to the d.p.c.m. coder can vary between the values 0 and 255.
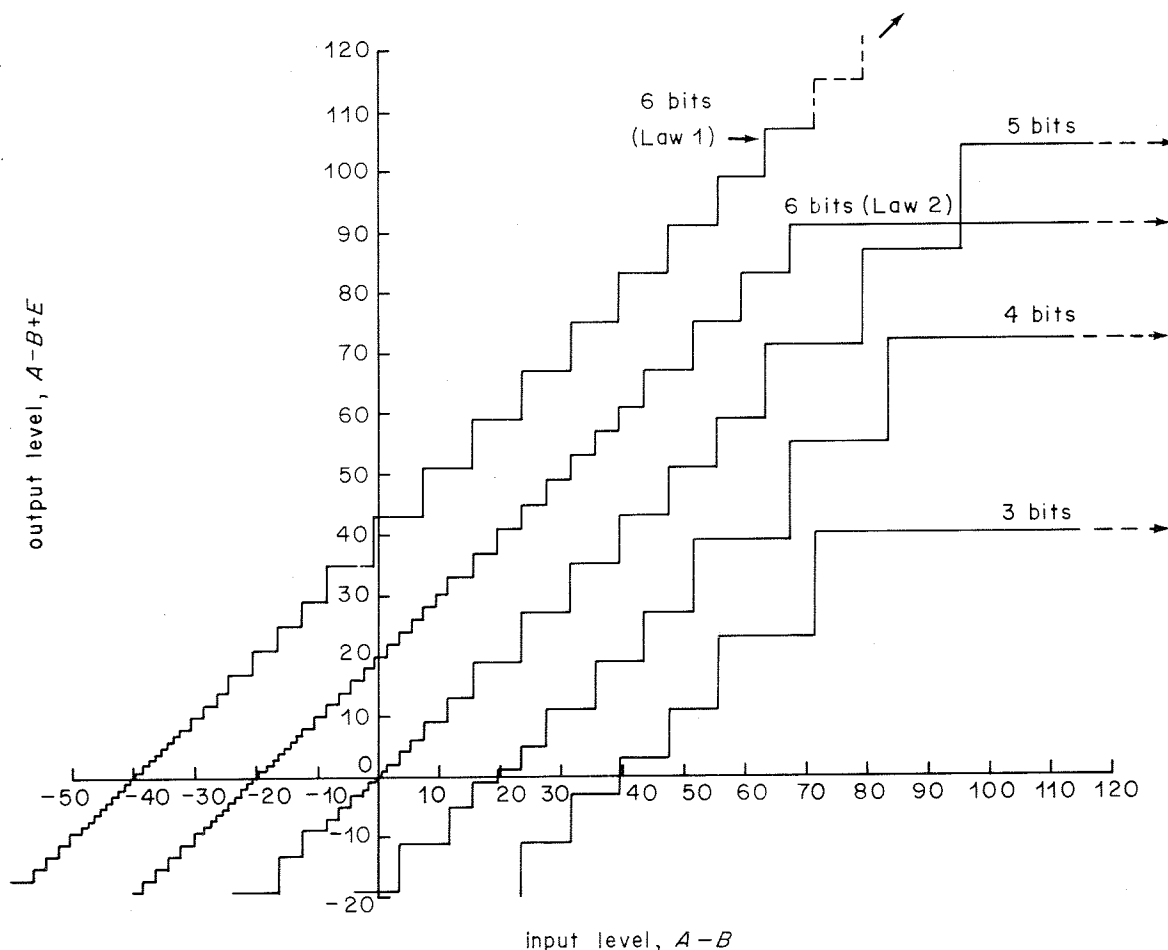


Fig. 8 - DPCM non-linear quantising laws calibrated in units of 8-bit p.c.m. quantum levels

For clarity, the 3, 4 and 6 bit laws are shifted horizontally by multiples of 20 quantum levels. In practice, all laws pass through the origin
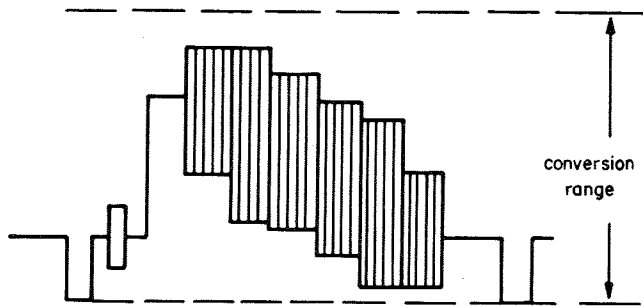
*Fig. 9 - Setting of video signal levels in relation to the conversion range of the 8-bit p.c.m. coder; shown for 100% colour-bars*

output levels which is the maximum number of different codes transmittable by means of 6 bits. This problem is overcome by an unambiguous method of using the same code to represent two output levels separated by a difference of ±256 as described in a previous report.[3] For all the remaining laws, the output difference values have a greatest magnitude which is much less than 255. The effect of this limitation was much less severe than might be expected, however, since the magnitude of a full black-to-white transition corresponded to a difference signal of only about 130; this difference between black and white levels was obtained because the magnitude of the video signal was adjusted, in all the d.p.c.m. tests, so that the peak-to-peak magnitude of a 100% colour bar signal was about 1 dB less than the conversion range of the p.c.m. coder used prior to the d.p.c.m. coder (see Fig. 9). This reduction in level avoided spurious operation of the d.p.c.m. codec which could occur with certain combinations of signal level and quantising error if the full conversion range was employed.[3]

For two-dimensional prediction, extra circuitry was added to a previously constructed same-line predictor to give the arrangement shown in Fig. 10. S1, S2, S3 and S5 in this figure were controlled manually by separate switches but S4 operated automatically depending on the positions of S2 and S3. With both S2 and S3 in the positions shown, S4 was set to position 'a'; otherwise S4 was set to position 'b'. Different combinations of these switches permit the following types of prediction.

(a) Same-line prediction corresponding to a delay of $T$ or $3T$ with unity gain.

(b) Previous-line prediction corresponding to the delay in the switched-line-delay in tandem with $T$ and $2T$ delays, with unity gain. The additional $3T$ delay was offset by reducing the delay of the fixed part of the line-delay to $(N-3)T$.

(c) Two-dimensional prediction corresponding to half the sum of the prediction signals given by $3T$ prediction and previous-line prediction.

The circuit used to obtain the fixed part of the line-delay consisted of eight 775-bit m.o.s. shift-registers clocked at $3 f_{sc}$, separate registers being used for each bit of an 8-bit p.c.m. video sample. In order to increase the delay provided by these registers from $775T$ to the required delay of about $847T$, a fixed number of successive clock-pulses were removed from the clock-pulse feed to the registers during each video line-blanking interval starting at the leading edge of the line-synchronising pulse.

## 6. Subjective tests

### 6.1. Test conditions

Subjective tests have been performed using the equipment described in Section 5 to examine the impairment of System I (PAL, 625-line, 5·5 MHz) video-signals resulting from d.p.c.m. coding of the composite signal, including synchronising pulses, at a sampling frequency of $3 f_{sc}$. Both two-dimensional (2D) prediction and third-previous-($3T$) prediction were examined. For two-dimensional prediction, predicted sample values were given by half the value of the third-previous sample on the same line plus half the value of the sample from the previous line corresponding to N = 850 (see Section 3). The d.p.c.m. quantising laws which were examined corresponded to those labelled 3, 4, 5 and 6 (Law 1) bits in Fig. 8. For comparison, tests were also carried out using p.c.m. coding with 4, 5, 6 and 7 bits per sample at the same sampling frequency and with dither[1] in use.
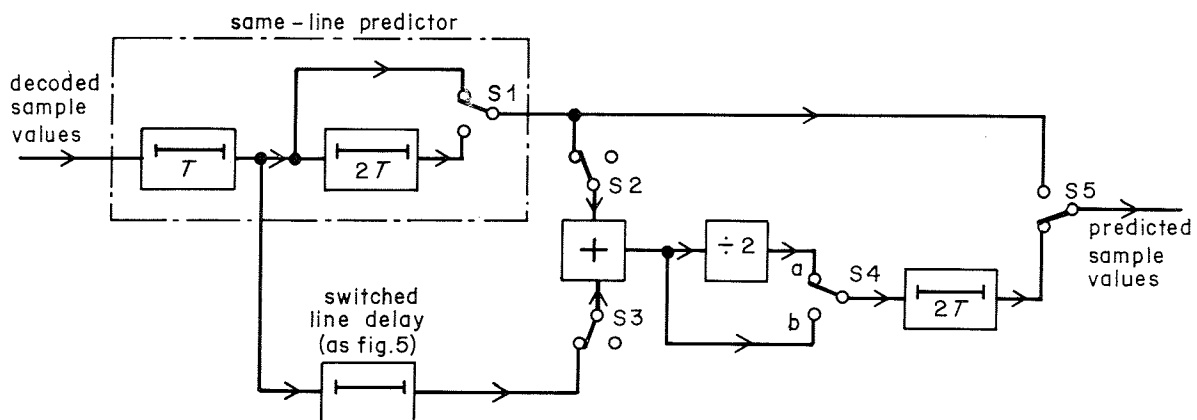


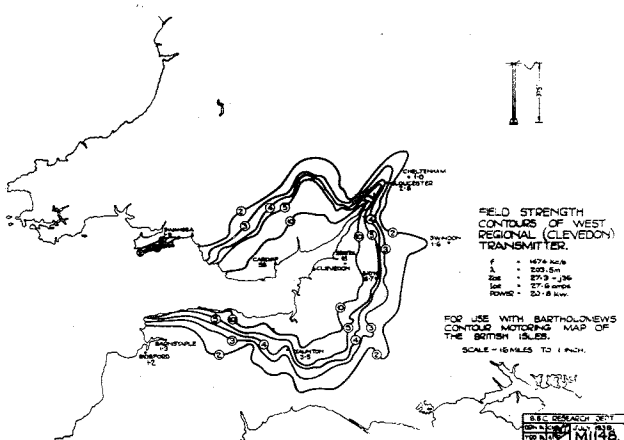*Fig. 10 - Predictor used in experimental equipment*

(a)



(b)



(c)



(d)

*Fig. 11 - Monochrome versions of slides used in subjective tests*

(a) Slide 2 - Car Park     (b) Slide 3 - Girl with headscarf     (c) Slide 4 - Boy with toys     (d) Slide 5 - Map

The video signals obtained from an 8-bit p.c.m. decoder following the d.p.c.m. coder ($A+E$ output, Fig. 1) were displayed on a high-quality colour-monitor with a screen diagonal of 560 mm (22 in.). The peak luminance of the monitor screen was adjusted to be 70 cd/m$^2$; with zero beam-current, the luminance of the screen resulting from ambient illumination was about 0·7 cd/m$^2$.

All the pictures examined were obtained from a high-quality 35 mm colour-slide flying-spot scanner. Five slides were used, these being selected to provide reasonably critical scenes for showing the forms of picture impairment to be expected. Monochrome versions of these slides are shown in Fig. 11 and Fig. 6(a).

### 6.2. Test procedure

Each test (processed) picture was shown twice to a group of eight observers seated at between four and six times picture-height from the monitor. The observers were all engineers experienced in assessing picture quality. Before the tests commenced, the type of impairment to be expected was pointed out to the observers. Each test condition consisted of the following sequence:— test picture, unprocessed analogue picture; test picture; unprocessed analogue picture. In each series of tests, signals processed by one and two-dimensional d.p.c.m. and by p.c.m. were shown in random order.

Picture quality was graded using the six-point impairment scale given below.*

* The CCIR has a new Recommendation 500 (1974) to use a five-point scale for assessing picture impairment. In this scale, Grade 5 corresponds to imperceptible impairment. As a first approximation, the linear relationship $A_5 = 5·8 - 0·8 A_6$ can be used to transform a six-point grade $A_6$ as used in this report into a CCIR five-point grade $A_5$.

| Grade | Degree of Impairment |
|-------|----------------------|
| 1 | Imperceptible |
| 2 | Just perceptible |
| 3 | Definitely perceptible but not disturbing |
| 4 | Somewhat objectionable |
| 5 | Definitely objectionable |
| 6 | Unusable |

## 6.3. Results

Details of the mean grades obtained for each test condition are given in Table 1. The figures in brackets indicate the standard deviation of the impairment grade resulting from changes in picture material. The mean values of the results for all pictures as given in the right-hand column of Table 1 are shown graphically in Fig. 12.

These results indicate that for a given impairment worse than about grade 2, the number of bits per sample required for d.p.c.m. with two-dimensional prediction is about one third of a bit less than for d.p.c.m. with third-previous-sample prediction, and about 1¾ bits less than for d.p.c.m. For high-quality pictures (better than grade 2) there appears to be a greater advantage in using two-dimensional prediction compared to third-previous sample prediction, although this trend might be due to experimental errors caused by insufficient observations. If grade 1·5 is taken as the maximum acceptable impairment for the transmission of broadcast-quality pictures, and considering only integral numbers of bits per sample, the results indicate that at least 5 bits per sample are required for two-dimensional d.p.c.m. compared to 6 bits for d.p.c.m. coding with third-previous-sample prediction and 7 bits for
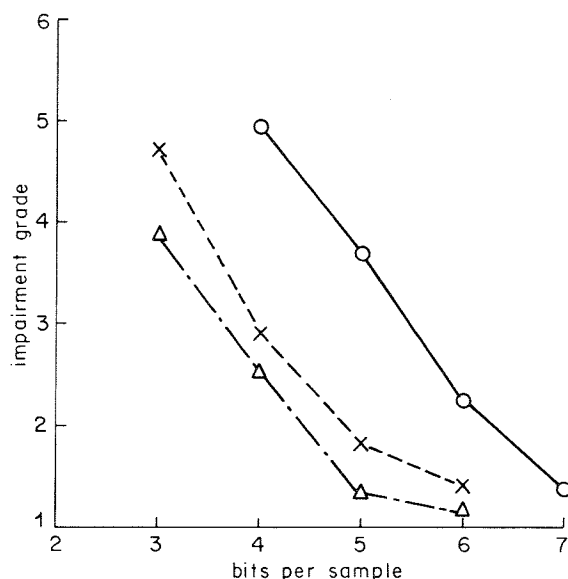


Fig. 12 - *Impairment versus bits per sample for d.p.c.m. and p.c.m. coding of PAL video signals*

O———————O   p.c.m.
X— — — —X   d.p.c.m. with 3$T$ prediction
△———·—△   d.p.c.m. with 2D prediction

p.c.m. coding. It should be noted that these results apply to only one codec (coding and decoding operation); it is reasonable to suppose that one extra bit per sample would be required to allow for up to four codecs in tandem.

In Fig. 13, the best results obtained so far for d.p.c.m. coding of PAL signals at a sampling frequency of 3 $f_{sc}$

## TABLE 1

### Results of Subjective Tests

| System (sampling at 3$f_{sc}$) | Bits per • sample | Mean Impairment Grade | | | | | |
|---|---|---|---|---|---|---|---|
| | | Slide Number | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | Mean |
| DPCM Same-line (3$T$) prediction | 3 | 5·11 | 4·28 | 4·39 | 4·72 | 5·11 | 4·72 (0·39) |
| | 4 | 2·78 | 2·72 | 3·28 | 2·89 | 2·83 | 2·90 (0·22) |
| | 5 | 1·89 | 1·83 | 1·89 | 1·50 | 1·89 | 1·80 (0·17) |
| | 6 (Law 1) | 1·66 | 1·32 | 1·38 | 1·33 | 1·32 | 1·40 (0·15) |
| DPCM Two-dimensional (2D) prediction | 3 | 4·11 | 3·78 | 3·89 | 3·94 | 3·72 | 3·89 (0·15) |
| | 4 | 2·33 | 2·67 | 2·78 | 2·72 | 2·11 | 2·52 (0·29) |
| | 5 | 1·72 | 1·22 | 1·39 | 1·11 | 1·22 | 1·33 (0·24) |
| | 6 (Law 1) | 1·28 | 1·00 | 1·11 | 1·00 | 1·22 | 1·12 (0·13) |
| PCM | 4 | 4·50 | 5·11 | 5·17 | 5·00 | 4·89 | 4·93 (0·27) |
| | 5 | 3·72 | 3·61 | 3·94 | 3·56 | 3·67 | 3·70 (0·15) |
| | 6 | 2·61 | 2·22 | 2·39 | 2·22 | 1·78 | 2·24 (0·30) |
| | 7 | 1·39 | 1·44 | 1·44 | 1·06 | 1·22 | 1·31 (0·17) |

Slide 1 - Test Card F        Slide 2 - Car Park        Slide 3 - Girl with Headscarf
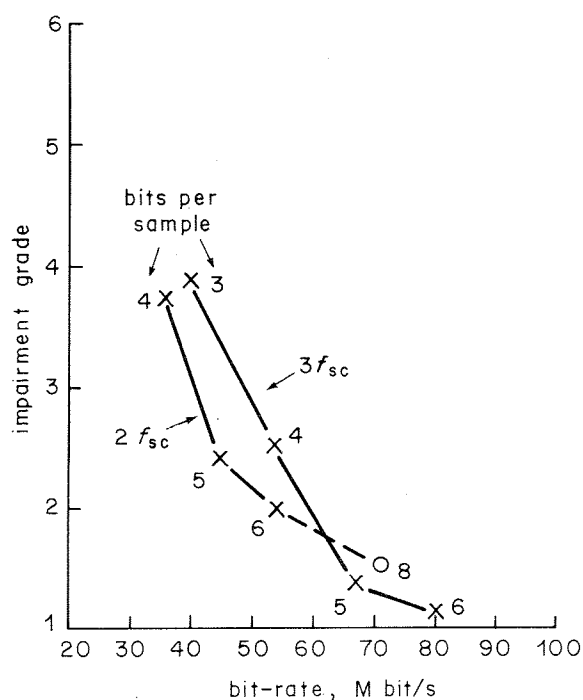Slide 4 - Boy with Toys        Slide 5 - Map

*Fig. 13 - Impairment versus bit-rate for d.p.c.m. coding of PAL signals with sampling frequencies of $2 f_{sc}$ and $3 f_{sc}$*

X results for d.p.c.m.　　　O result for p.c.m.

(i.e. d.p.c.m. with two-dimensional prediction) are compared with the results obtained in previous tests for d.p.c.m. and p.c.m. coding at a sub-Nyquist sampling frequency of $2 f_{sc}$.[7] For $2 f_{sc}$ sampling, second-previous sample ($2T$) prediction was used, i.e. that given by the sample occurring one subcarrier-cycle earlier in the same line as an incoming sample; previous-line prediction was not used. (Previous-line prediction would be more difficult to arrange because the amplitude of the chrominance component of a PAL signal after sampling at $2 f_{sc}$ alternates between $U+V$ and $U-V$ on successive lines.) The impairment of grade 1·5 for 8-bit p.c.m. at a sampling frequency of $2 f_{sc}$ probably indicates the basic impairments caused by the video comb-filters required by the sub-Nyquist sampling process, quantising errors being virtaully imperceptible with this coding system. By comparing the curves for $2 f_{sc}$ and $3 f_{sc}$ it can be seen that there is a cross-over point at about 60 Mbit/s. Below this point, the $2 f_{sc}$ systems which have been examined give better results while above it the best $3 f_{sc}$ systems examined so far give less impairment.

## 7. An adaptive same-line predictor

After the completion of the tests described so far, control circuitry for an adaptive same-line predictor was used in conjunction with a 5-bit non-linear quantiser having the law shown in Fig. 8. This adaptive mode of prediction was designed as an attempt to achieve a more accurate same-line prediction during rapid luminance transitions than that obtained during third-previous sample ($3T$) prediction alone. The basic principle of operation was that previous sample ($1T$) prediction was used for the three samples following the occurrence of a large difference ($\geqslant \pm 16$ quantum levels)

with the $3T$ prediction in use; the $3T$ prediction was then re-inserted until the next large difference was obtained, when the process was repeated. Additionally, if a very large difference ($\geqslant \pm 64$ quantum levels) occurred with $1T$ prediction is use, the prediction was forced into the $3T$ mode for up to four samples following the three samples in the $1T$ mode; this extra condition prevented the incorrect selection of the $1T$ mode following a rapid change between saturated colours which could occur for reasons explained in a previous report.[3] By setting the coder and decoder to follow the same rules, it is unnecessary to transmit any information to indicate which form of prediction is in use.

No formal subjective tests have been performed so far using this adaptive $1T/3T$ prediction. Informal tests were inconclusive regarding any difference in picture quality compared to $3T$ prediction alone, but this was not altogether unexpected since the mean impairment for $3T$ prediction at 5 bits per sample was only grade 1·8, leaving little scope for improvement in subjective terms. Measurements of quantising and prediction errors discussed in Sections 8 and 9 indicate, however, that adaptive prediction gives a similar improvement to that given by two-dimensional prediction; further work would be necessary to check whether this reduction in quantising errors is reflected by a corresponding improvement in subjective terms.

## 8. Measurement of signal-to-quantising-noise ratio to compare d.p.c.m. and p.c.m. coding

In order to provide additional information concerning the effects of d.p.c.m., the equipment used for the subjective tests included a subtractor giving the difference between the 8-bit p.c.m. input and output signals of the d.p.c.m. coder, i.e. the output of this subtractor gave the quantising error ($E$ in Fig. 1) caused by d.p.c.m. coding. After conversion into analogue form, the r.m.s. magnitude of this d.p.c.m. quantising error was measured under various test conditions by means of a thermo-couple device included in a conventional analogue-video signal-to-noise-ratio meter. The values obtained for unweighted signal-to-quantising noise ratios are given in Table 2, together with similar measurements for p.c.m. coding with dither in use, (i.e. the quantising noise signal corresponding to the difference between an 8-bit p.c.m. signal and a p.c.m. signal with a reduced number of bits per sample). For all these measurements, the magnitude of the video signal relative to the p.c.m. coding range was adjusted as indicated in Fig. 9.

As is usual with video signal-to-noise-ratio measurements, the signal magnitude was taken as the difference in voltage between the black and white levels of the video signal while r.m.s. values were used for noise magnitudes, the noise bandwidth being limited to the frequency range 10 kHz to 5 MHz.

Examination with a spectrum analyser showed that the quantising errors caused by both p.c.m. and d.p.c.m. has a substantially flat amplitude-spectrum from 0 to 5·5 MHz.

TABLE 2

*Measurements of Signal-to-Quantising-Noise Ratios for d.p.c.m. and p.c.m. Coding*

| System | Bits per sample | Signal-to-quantising noise ratio | | | | | |
|---|---|---|---|---|---|---|---|
| | | Slide number | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | Mean |
| DPCM same-line 3*T* prediction 1*T*/3*T* | 3 | 27·7 | 33·5 | 34·1 | 33·5 | 33·1 | 32·4 |
| | 4 | 34·5 | 40·0 | 42·3 | 40·8 | 40·0 | 39·5 |
| | 5 | 41·2 | 44·0 | 47·2 | 45·2 | 45·0 | 44·5 |
| | 6 (Law 1) | 44·8 | 46·9 | 51·0 | 48·3 | 48·5 | 47·9 |
| | 6 (Law 2) | 45·0 | 51·0 | 54·5 | 52·4 | 49·9 | 50·6 |
| | 5 | 43·5 | 44·6 | 47·7 | 46·1 | 46·5 | 45·7 |
| DPCM Two-dimensional (2D) prediction | 3 | 33·2 | 34·8 | 35·0 | 35·2 | 35·7 | 34·8 |
| | 4 | 39·0 | 41·0 | 43·6 | 42·0 | 41·8 | 41·5 |
| | 5 | 42·7 | 44·5 | 49·0 | 46·2 | 45·7 | 45·6 |
| | 6 (Law 1) | 45·5 | 48·7 | 53·8 | 50·6 | 49·2 | 49·6 |
| | 6 (Law 2) | 49·3 | 52·8 | 57·5 | 54·7 | 53·0 | 53·5 |
| PCM | 4 | Measurements varied by only about ±0·1 dB for different slides | | | | | 29·7 |
| | 5 | | | | | | 35·8 |
| | 6 | | | | | | 41·5 |
| | 7 | | | | | | 48·5 |

Slide 1 - Test Card     Slide 2 - Car Park     Slide 3 - Girl with Headscarf
Slide 4 - Boy with Toys     Slide 5 - Map

The instrumental conditions for noise measurements were the same as those used in the subjective tests except that, for reasons explained below, measurements were made using an additional 6-bit d.p.c.m. quantising law. It is thus possible to plot impairment versus signal-to-quantising-noise ratio for d.p.c.m. and p.c.m. systems, as shown in Figs. 14, 15, 16 and 17. The corrected horizontal scale on Fig. 14 includes an allowance for 8-bit p.c.m. quantising noise, and thus it applies to the total quantising noise caused by both d.p.c.m. and p.c.m. coding; the assumed signal-to-quantising-noise ratio for 8-bit p.c.m. was 52 dB (unweighted)[1]
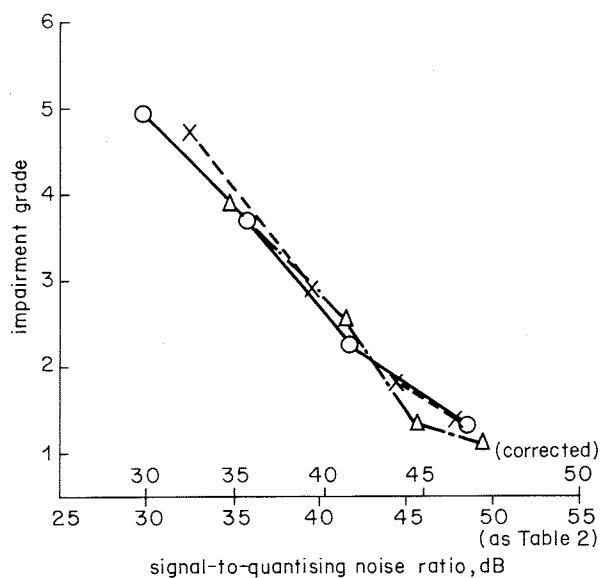


*Fig. 14 - Impairment versus signal-to-quantising noise ratio for d.p.c.m. and p.c.m.; mean results for all slides*

O——O p.c.m.
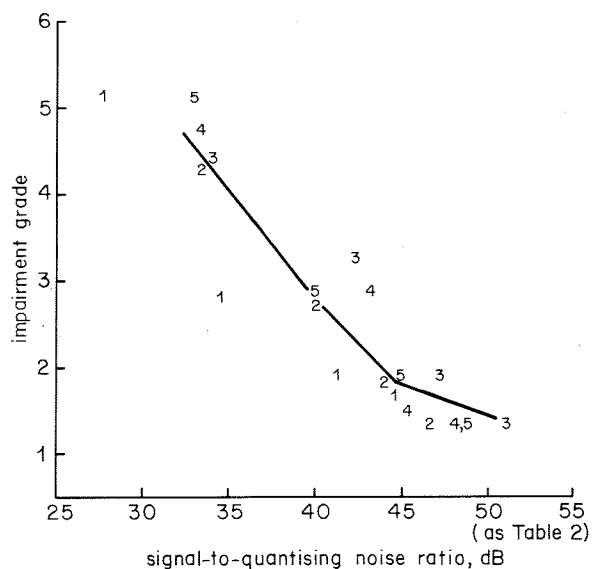X— — —X d.p.c.m. with 3*T* prediction
Δ—·—Δ d.p.c.m. with 2D prediction



*Fig. 15 - Impairment versus signal-to-quantising noise ratio for d.p.c.m. with 3T prediction. Results for individual slides*

1, 2, 3, 4, 5 refer to slides 1, 2, 3, 4, 5
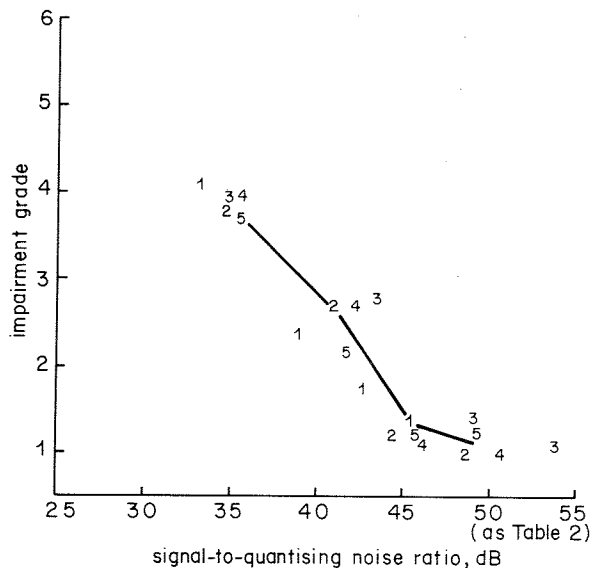———— connects mean values for all slides

*Fig. 16 - Impairment versus signal-to-quantising-noise ratio for d.p.c.m. with two-dimensional prediction. Results for individual slides*

1, 2, 3, 4, 5 refer to slides 1, 2, 3, 4, 5

——————— connects mean values for all slides



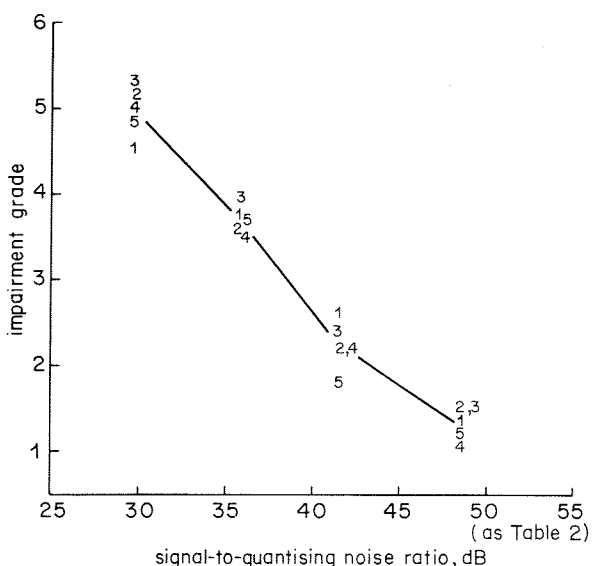*Fig. 17 - Impairment versus signal-to-quantising-noise ratio for p.c.m. Results for individual slides*

1, 2, 3, 4, 5 refer to slides 1, 2, 3, 4, 5

——————— connects mean values for all slides

which includes an allowance of 3 dB for instrumental imperfections.

The results shown in Fig. 14 indicate that the impairment grade obtained for a given signal-to-quantising-noise ratio is generally similar for p.c.m. and d.p.c.m. This conclusion is contrary to the often expressed opinion that quantising errors occurring on sharp transitions in picture detail (as produced by d.p.c.m.) are less visible than quantising errors of the same power which occur uniformly over the whole picture area (as produced by p.c.m.). It may be relevant that arguments concerning the relatively low visibility of errors on sharp transitions are often based on considerations of steady-state errors whereas in a practical television system, the majority of quantising errors fluctuate with time, even on a 'still' picture, due to the presence of random noise. It should be mentioned that although the results given in Fig. 14 show that measurements of quantising noise in general give a good indication of picture impairment, it is important not to place too much reliance on these measurements as an absolute guide to picture quality since other factors such as the type of scene being displayed must also be taken into account. The results given in Figs. 15 and 16, when compared with those in Fig. 17, indicate that the visibility of d.p.c.m. quantising noise is more dependent on picture content than p.c.m. quantising noise. However, only one slide (Slide 1 — Test Card F) gave results for which d.p.c.m. quantising errors were significantly less visible than an equal power of p.c.m. quantising errors.

The measurements for 6-bit d.p.c.m. using Law 2 were performed because it was noticed that the improvement in signal-to-quantising-noise using Law 1 compared to that for the 5 bit d.p.c.m. system was significantly less than the figure of 6 dB which might be expected as a result of doubling the number of quantum levels. Examination of prediction errors indicated that Law 2 should give a smaller r.m.s. quantising error than Law 1 and the results in Table 2 show that this supposition was correct. Law 1 had the advantage, however, that the maximum difference which could be transmitted by a single code was equal to the full conversion range of the p.c.m. encoder whereas the maximum difference with Law 2 was only about 2/3 of the black-to-white magnitude of the PAL video signal adjusted as shown in Fig. 9. Law 1 should thus be more suitable for coding critical pictures containing many sharp black-to-white transitions such as those given by printed text. Further subjective tests were not carried out using Law 2 because informal tests indicated that there was no noticeable difference between the picture qualities obtained with the two laws for only one coding and decoding process. It is possible, however, that the advantage of the lower signal-to-noise ratio given by Law 2 might be significant after several coding and decoding operations connected in tandem.

The results given in the right-hand column of Table 2 are shown in graphical form in Fig. 18. From this figure it can be seen that, at a given number of bits per sample the r.m.s. quantising errors given by d.p.c.m. with two-dimensional prediction were on average about 2 dB less than those given by d.p.c.m. with third-previous-sample prediction and about 11 dB less than those given by p.c.m. It should be noted that an increase of 6 dB in the signal-to-quantising noise ratio corresponds to increasing the number of bits per sample by one.

In a previous report,[1] it was shown that a p.c.m. system with 3 $f_{sc}$ sampling required 8 bits per sample in order that the r.m.s. quantising noise obtained from four codecs in tandem should satisfy signal-to-noise ratio specifications for the transmission of System I broadcast-quality pictures (i.e. 52 dB, luminance weighted, and 46 dB,
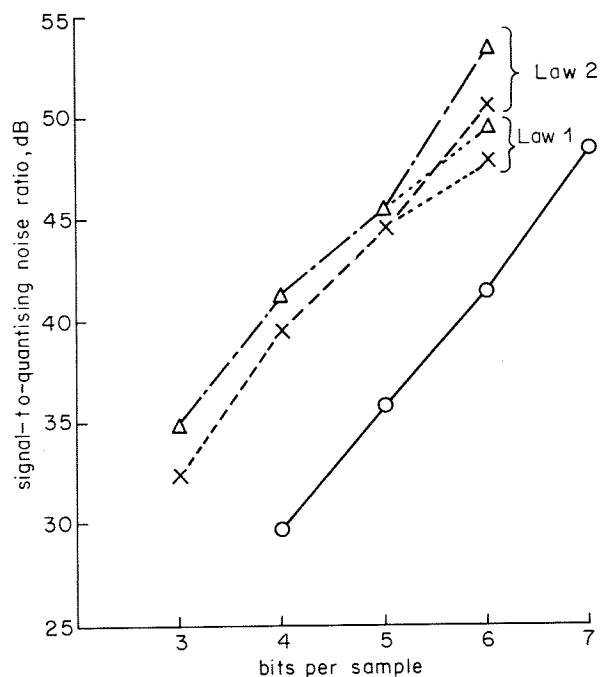
*Fig. 18 - Mean values of signal-to-quantising-noise ratio versus bits per sample for d.p.c.m. and p.c.m. coding*

O———O p.c.m.

X— — —X d.p.c.m. with $3T$ prediction

△—·—△ d.p.c.m. with 2D prediction

chrominance weighted).* Therefore, using this criterion for digital transmission, and assuming that a given signal-to-quantising noise ratio corresponds to the same picture impairment for both d.p.c.m. and p.c.m. coding, the differences between the p.c.m. and d.p.c.m. signal-to-quantising-noise ratios given above indicate that 6 bits per sample (Law 2) should be satisfactory for d.p.c.m. coding with two-dimensional prediction but 7 bits per sample may be required for third previous sample prediction. These figures are in substantial agreement with the results of the subjective tests.

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* System I hypothetical reference circuit, CCIR Rec. 451. For white noise, the given specifications are equivalent to an unweighted signal-to-noise ratio of 45·5 dB.

The measurements of signal-to-quantising-noise ratio using $1T/3T$ adaptive prediction given in Table 2 show that this form of prediction reduced the r.m.s. quantising noise for all the test slides, the reduction being similar to that given by 2D prediction.

## 9. Measurements of prediction errors

As a further indication of the relative effectiveness of different forms of prediction, measurements were made on the r.m.s. magnitude of the prediction-error signal. (Prediction error is represented by $A-B$ in Fig. 1 whereas quantising error is represented by $E$.) The results obtained for signal-to-prediction-error ratios (unweighted) are given in Table 3. The quantising law in use for these measurements was the 5-bit law, but this fact is not very significant since changing the number of bits per sample has very little effect on the magnitude of the prediction error, providing the law corresponds to at least 3 bits per sample.

The results given in Table 3 indicate again that $1T/3T$ prediction should have a similar effect to 2D prediction in reducing errors in a d.p.c.m. system. Also it will be seen that the reduction in prediction errors given by $1T/3T$ and 2D prediction compared to $3T$ prediction is slightly greater than the corresponding reduction in quantising noise given in Table 2 except for 6 bits, Law 2. This suggests that the quantising laws used in the tests may have been more suitable for $3T$ prediction than for $1T/3T$ or 2D prediction, but it is doubtful if the use of different laws for $1T/3T$ and 2D prediction would have a significant effect on picture quality. This conclusion is corroborated by theoretical work concerning the relationship between r.m.s. prediction errors and r.m.s. quantising noise for quantising laws optimised to give minimum r.m.s. quantising noise. This relationship is discussed in the Appendix. The Appendix also gives a method of deriving optimum quantising laws from measurements of prediction errors. This theoretical work indicates that the quantising laws used in the subjective tests were in general a reasonable compromise between the optimum laws required by the different scenes and prediction methods. It is possible, however, that a just-noticeable improvement in picture quality might be obtained by modifying the 5-bit law for use with $1T/3T$ and with 2D predictions. The advantage of Law 2 for 6-bits per sample compared with Law 1 in regard to minimising quantising errors is again apparent as discussed in Section 8.

*TABLE 3*

*Measurements of Signal-to-Prediction Error Ratio*

| DPCM Prediction | | Signal-to-prediction-error ratio (dB) | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | Slide number | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | Mean |
| Same-line — $3T$ | | 15·7 | 20·4 | 23·7 | 21·7 | 20·8 | 20·5 |
| Same-line, adaptive $1T/3T$ | | 20·4 | 22·8 | 26·0 | 24·5 | 24·8 | 23·7 |
| Two-dimensional (2D) | | 17·3 | 22·4 | 27·3 | 24·6 | 23·9 | 23·1 |

# 10. Conclusions

This report has described a novel technique for predicting sample-values of a PAL video signal from samples occurring in the previous line of the same field. The technique has been applied in d.p.c.m. equipment employing two-dimensional prediction, and results have been given of subjective tests concerning the impairment of System I (PAL, 625-line, 5·5 MHz) video signals which is introduced by this equipment. These results are compared with results obtained for d.p.c.m. coding with same-line prediction and for p.c.m. coding. The above-mentioned forms of coding have also been compared by means of measurements of r.m.s. quantising noise and prediction errors. The sampling frequency employed for all coding systems was three times the PAL colour subcarrier frequency.

The results of both subjective tests and measurements of quantising errors indicate that for a given picture impairment, the number of bits per sample required for d.p.c.m. with two-dimensional prediction is about one third of a bit less than for d.p.c.m. with third-previous-sample prediction, and about 1¾ bits less than for p.c.m. The results indicate also that in order to obtain broadcast-quality pictures after four d.p.c.m. coding and decoding processes connected in tandem, 6 bits per sample would be satisfactory if two-dimensional prediction is employed but an extra bit per sample may be required for third-previous sample prediction. However, if only one codec is used, then the number of bits per sample could probably be reduced to five for two-dimensional and six for third-previous-sample predictions, to obtain broadcast-quality pictures.

Measurements of both quantising noise and prediction errors indicate that marginally improved results may be obtained for two-dimensional prediction by modifications to the quantising law. Similar measurements also showed that an adaptive same-line predictor, which has been described, is capable of reducing r.m.s. quantising and prediction errors, compared with those given by third-previous-sample prediction, to about the same extent as two-dimensional prediction. Formal subjective tests have not yet been performed to determine whether a corresponding improvement can be obtained in picture quality with this adaptive predictor; informal tests were inconclusive.

A comparison of subjective test results and measurements of quantising noise for d.p.c.m. and p.c.m. coding indicated that the picture impairment corresponding to a given signal-to-quantising-noise ratio (the noise being averaged over the picture) was similar, in general, for both p.c.m. and d.p.c.m. coding. This conclusion is contrary to the often expressed opinion that d.p.c.m. quantising errors are less visible than p.c.m. quantising errors, by virtue of the fact that the former are concentrated on sharp transitions

in picture detail, rather than being uniformly spread over the whole picture area as in p.c.m. It should be noted, however, that the visibility of quantising errors were more dependent on picture content for d.p.c.m. than for p.c.m.

# 11. References

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# 12. Appendix: Examination of Quantising Laws Based on Measurements of Prediction Errors and Quantising Noise

## 12.1. Use of prediction-error measurements

If the value of the r.m.s. prediction-error $\sigma_e$ is known, it is possible to determine theoretically the quantising-law giving the minimum possible r.m.s. quantising-error for a given number of bits per sample n and given maximum prediction-errors $\pm M$. O'Neal[2] has given the theoretical equations given below which assume that the prediction-errors have a Laplacian probability distribution;* this has been found to be a reasonable assumption for the type of errors considered in this report.[2,8] The magnitudes of the output of the quantiser $y(z)$ corresponding to each of the $2^n$ output levels of this optimum quantising law are given by the equations:—

$$y(z) = -\frac{3\sigma_e}{\sqrt{2}} \log_e \left[ 1 - \frac{z}{M}\left( 1 - \exp\left(\frac{-\sqrt{2}M}{3\sigma_e}\right)\right)\right] \text{ for } z \geqslant 0$$

$$y(-z) = -y(z)$$

(1)

where $z$ has $2^n$ values equally spaced between $+M$ and $-M$ given by:—

$$2^n \cdot \frac{z}{M} = -(2^n - 1), -(2^n - 3), \ldots (2^n - 3), (2^n - 1) \quad (2)$$

Using the mean values of prediction error given in Table 3, it can be calculated that $\sigma_e$ = 12·3 and 9·09 quanta** for $3T$ and 2D prediction respectively. To obtain these values of $\sigma_e$, a value of 130 quanta was used for the black-to-white magnitude of the video signal (see Section 4). Assuming that $M$ also equals 130 quantum levels, the resulting relationships between $y(z)$ and $z/M$ for a 5-bit quantising law and $3T$ prediction (i.e. $\sigma_e$ = 12·3) are shown in Table 4 for positive values of $z$. The negative half of the law, is given by changing the signs of both $z/M$ and $y(z)$. The input decision levels of this law would lie half-way between adjacent values of output quantum levels.[10]

For comparison with the 5-bit quantising law used in practice, Table 4 includes the values of the positive output levels of the 5-bit law given in Fig. 8. For convenience, the $r$th largest output levels of both the theoretical and practical laws have been shown in the same row. It is thus possible to associate a value of $z/M$ with each of the output levels of the practical laws as required below.

---

* For a Laplacian probability distribution, the probability $P(e)$ of a prediction error of magnitude $e$ is given by

$$P(e) = \frac{1}{\sqrt{2}\sigma_e} \cdot \exp\left(\frac{-\sqrt{2}}{\sigma_e}|e|\right)$$

** 1 quantum = spacing between adjacent 8-bit p.c.m. quantum levels as in Section 5.

## TABLE 4

*Comparison of 5-bit theoretical and practical quantising laws*

| $z/M$ | $y(z)$ Output levels for theoretical law | Output levels for practical law |
|---|---|---|
| 31/32 | 85·3 | 104 |
| 29/32 | 60·0 | 87 |
| 27/32 | 47·4 | 71 |
| 25/32 | 39·0 | 59 |
| 23/32 | 32·6 | 51 |
| 21/32 | 27·5 | 43 |
| 19/32 | 23·2 | 35 |
| 17/32 | 19·6 | 27 |
| 15/32 | 16·3 | 19 |
| 13/32 | 13·5 | 13 |
| 11/32 | 10·9 | 9 |
| 9/32 | 8·5 | 6 |
| 7/32 | 6·4 | 4 |
| 5/32 | 4·4 | 2 |
| 3/32 | 2·6 | 1 |
| 1/32 | 0·8 | 0 |

A graphical comparison of theoretical and practical quantising laws is shown in Fig. 19. The theoretical curves in this Figure are obtained from Equation (1) and are applicable to any number of bits per sample n; for a given n, the appropriate output levels correspond to the values of $z/M$ given by Equation (2). For the practical laws, the values of $z/M$ corresponding to each output level were obtained in the manner indicated for Table 4. The practical laws used for 3 and 4 bits per sample closely follow the characteristics given in Fig. 19 for 6 bits (Law 2) and 2D prediction respectively.
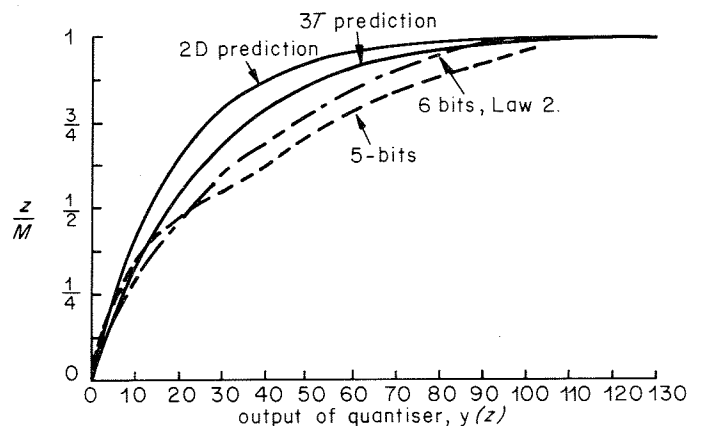


Fig. 19 - Characteristics of calculated and practical quantising laws. Horizontal axis calibrated in units of 8-bit p.c.m. quantum levels. Output levels occur at values of $z/M$ equally spaced between 0 and 1
——————— Calculated laws    ‑ ‑ ‑ ‑ ‑ ‑ ‑ Laws used in tests

The most noticeable difference between the practical and calculated laws shown in Fig. 19 is that the output levels for large prediction errors have been set to higher values in the practical laws (i.e. for high values of $z/M$, $y(z)$ is greater for the practical than for the theoretical laws). A good reason for this departure from the calculated laws is that it allows more accurate quantising of critical scenes such as graphics which include a high proportion of high amplitude prediction errors.

A similar departure from the calculated laws has been suggested by Candy and Bosworth;[11] their results are not expressed in quite the same form, however, as they plotted the manner in which quantising noise should depend on the slope of the video signal, (i.e. on the magnitude of the prediction error). An equivalent technique is to plot the difference between adjacent output quantum levels against the mean value of these adjacent quantum levels; a graph of this form is shown in Fig. 20 for the calculated and practical 5-bit laws. It can be seen that this form of graph shows up differences in characteristics for small values of the quantiser output (i.e. small prediction errors) more clearly than Fig. 19. The general shape of the practical law in this figure bears a marked resemblance to the optimum law suggested by Candy and Bosworth for accommodating a variety of scenes. They found that the quantising law (plotted as in Fig. 20) should have zero gradient for medium-size prediction-errors in order to deal satisfactorily with graphical types of scene.

## 12.2. Comparison of measured values of quantising noise and prediction-errors

Further information concerning the suitability of the quantising laws used in the subjective tests can be obtained by comparing measured values of signal-to-quantising-noise

ratios (see Table 2) with theoretical maximum values of these ratios obtainable with the optimum quantising laws discussed in Section 12.1. These theoretical values of r.m.s. quantising noise can be calculated from measurements of signal-to-prediction error ratios (see Table 3) using an equation given by O'Neal (Equation (15) of Ref. 2) which can be re-arranged as:—

$$S/N_q = S/N_e + 6n - 6.5 \qquad (3)$$

where $S/N_q$ is the theoretical maximum value of signal-to-quantising-noise (in dB) for a given signal-to-prediction error ratio $S/N_e$ (in dB) and n is the number of bits per sample required by the quantising law. This equation assumes that the prediction errors have a Laplacian probability distribution (see Section 12.1).

The differences between measured values of the mean signal-to-quantising-noise ratios given in Table 2 and values calculated from Equation (3) and Table 3 are shown in Fig. 21. The results given in this Figure indicate that all the quantising laws were close to an optimum so far as minimisation of quantising errors is concerned. It is not very significant that some of the measured values of the signal-to-quantising-noise ratio were higher than is theoretically possible since some allowance must be made for experimental error; also, the assumption of a Laplacian probability distribution for prediction errors is not entirely correct. The fact that most of the points in Fig. 21 for 2D prediction lie below those for $3T$ prediction indicates that the quantising laws used in the tests were nearer an optimum for $3T$ than for 2D prediction. In particular it would appear that the 5-bit law could be adjusted to give a worthwhile improvement in the signal-to-quantising-noise ratios obtained with both $1T/3T$ and 2D prediction. The advantage of using Law 2 for 6 bits per sample compared to Law 1 is again apparent as discussed previously in Section 8.
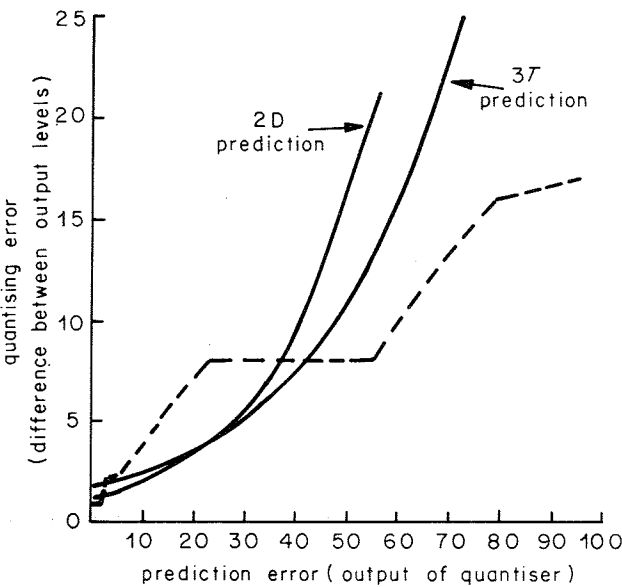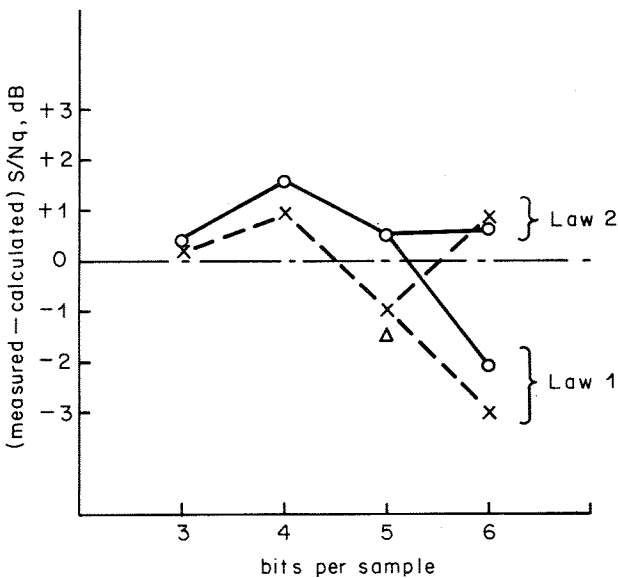


Fig. 20 - Diagram illustrating increase of quantising noise (difference between output levels) as prediction error (output of quantiser) increases for 5-bit quantising laws. (Calibrated in units of 8-bit p.c.m. quantum levels.)
——— Calculated laws   ————— Law used in tests



Fig. 21 - Comparison of measured and theoretical signal-to-quantising-noise ratios
o——o 3T prediction   x——x 2D prediction
Δ   1T/3T prediction

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